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SEISMIC MOTION STABILITY, MEASUREMENT AND PRECISION CONTROL

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FINAL REPORT

BILL J. SIMMONS

PROJECT 2304

AIR FORCE SYSTEMS COMMAND

UNITED STATES AIR FORCE

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The basis for a stable, low level motion test pad is a pneumatically supported, actively controlled Isolation Test Pad (Iso-pad). A number of tasks have been completed under this work unit, and other tasks have been supported by use of the "Iso-pad" and related equipment as a research tool. Also, there were research accomplishments on the Iso-pad, under an earlier work unit on advanced techniques for inertial guidance sensors testing. This final report presents the significant highlights, objectives, performance, and accomplishments of the research tasks completed. The performance is shown of the Iso-pad in the

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20. Abstract (continued)

concluding, low maintenance configuration as available for research tasks which require a low level vibration environment, or a precisely known motion excitation. Conclusions are drawn which relate final performance and improvement potential to tests of future inertial instruments, and the motion environment which may be required. A bibliography of presentations and publications which are based on the various phases of Iso-pad development are presented.

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TABLE OF CONTENTS

SEISMIC MOTION STABILITY, MEASUREMENT AND PRECISION CONTROL

FINAL REPORT

1. INTRODUCTION

This report describes the design and performance of an isolated test platform (Iso-pad) at the USAF Academy's Guidance and Control Laboratory, in use on testing and research programs of inertial navigation components and systems.

The Guidance and Control Laboratory is jointly operated by the Department of Astronautics and Computer Science and the Guidance and Control Division of the Frank J. Seiler Research Laboratory (FJSRL), an AFSC lab based at the Academy. The laboratory provides a facility for testing and research in state-of-the-art inertial guidance equipment.

The initial installation of the Iso-pad as a passive stable test base was in 1969. Beginning in about mid-1971, with recognition of the need for greater motion stability of a test base as a result of the predicted performance improvements of the 'third generation inertial instruments', there were modifications to improve the Iso-pad stability. Stability improvement through the technique of 'active control' has been accomplished under work unit 2304-F2-63 and an earlier effort, 2304-F2-43, pertaining to advanced testing techniques. There have also been a number of Iso-pad related efforts completed on which the Iso-pad was the tool for providing the necessary motion environment - either as a stable test base or as a precise motion exciter, as appropriate.

A brief summary of Iso-pad improvement tasks, and the associated efforts for which the Iso-pad was a required tool, is included, as well as a bibliography of the resultant papers and reports.

2. OBJECTIVES

The work unit, 2304-F2-63, Seismic Motion Stability, Measurement, and Precision Control, was initiated in September 1976. The task 'short title' identifier is 'Seismic Pad Control' (or unofficially Iso-pad). The following elements apply:

2.1 Deficiency

There exists an inability to evaluate low-noise, precision sensors, especially those instruments capable of satisfying current inertial guidance requirments.

2.2 Objectives

1. Investigate methods of actively controlling a 450,000 lb. air-suspended inertial test platform so as to minimize external disturbances. Design goals: less than 10^{-8}g linear motion, 0.001 arc sec tilt, and less than 10^{-4} deg/hr angular motion at a frequency of 1 rad/sec. This stability will allow realistic evaluation of state-of-the-art motion sensors.

2. Provision the active control servos to accept function drive signals for operating the Iso-pad as a precision, low-level motion exciter of test specimen instruments and systems.

3. A number of additional benefits are anticipated as by-products to the main efforts on the aforementioned objectives; these include cadet and faculty research tasks, improved test techniques, and support of advanced instrument research.

3. BACKGROUND

3.1 Iso-pad Location

The Iso-pad is located on the ground floor of the six floor building which houses the Academy's academic program including classrooms,

labortories, and faculty offices (Fairchild Hall). There are parking lots, light vehicle traffic, building heating, and air conditioning equipment within 100 ft. of the Iso-pad. Although the entire area is remote from heavy industry disturbances, it is clear that a considerable amount of motion noise is created in the proximity of the test facility.

Figure 1 shows the layout of the laboratory. Note the nine test piers which are an integral part of the Iso-pad; the bulk of the Iso-pad is housed in a room below the inner laboratory. The test piers protrude through holes in the laboratory's false floor. The "sealed" inner laboratory, designed as a Class 10,000 clean room, covers about 2,200 square feet of floor space; this sealed Iso-pad area has separate air conditioning ($67^o \pm 1^oF$) and air lock entry.

The primary azimuth reference used for precision alignment of test fixtures and components is a porro prism mounted within the inner laboratory. The orientation of this prism is ascertained, using autocollimating theodolites, either by directly "swinging" Polaris into the laboratory from outside through optical ports in the east wall or by reference to external permanent monuments from which the azimuth of each base leg can be independently verified. Base line survey, as well as latitude and longitude and measurement of gravity magnitude and deflection of the vertical, are provided by the Air Force's Geodetic Survey Squadron, located at Warren AFB, WY.

3.2 Pneumatic System Installation

The Iso-pad at the USAF Academy is constructed of steel reinforced concrete. The pictorial sketch, Figure 2, shows main equipment items and construction features of the Iso-pad. The Iso-pad is located in a subfloor room beneath the inner laboratory, with nine integral test piers

protruding upward through the "false" floor of the inner laboratory. It appears as a twenty-five foot square from the top with nine circular piers rising 2.5 ft. up from the main block of the Iso-pad. These piers are tied to the main block with reinforcing bars and were poured monolithically with the block. The bottom of the block has a cruciform shape that is 4.5 ft. high; this allows for location of the means of Iso-pad "lift." The total platform weight of 450,000 lbs. is supported by twenty pneumatic isolators, "actuators," and floated approximately 1/2 inch above the base slab. The peculiar shape of the block causes its center of gravity to be located near the level of the supporting pistons. In addition to the shape, hollow sonotubes buried in the upper slab portion of the block contribute to the proper location of the center of gravity, so as to minimize the coupling between the various modes of vibration as well as provide selected resonance characteristics.

The base slab which supports the pneumatic isolators is 24 in. reinforced concrete on grade of 4,000 psi compressive strength. The slab, or seismic mass, which is physcially distinct from the concrete basement floor around it, rests on a compacted aggregate fill three ft. in thickness. This three ft. base course is separated from the subgrade by a continuous polyethylene vapor barrier layed over a two inch concrete base placed on the subgrade. The subgrade itself is a native granular cohesionless decomposed granite material (natural formation, not fill). Professor Ken Tsutsumi of Tufts University specified the base design.

The isolation/control system on the original installation was designed and installed by the Barry Controls Division of the Barry-Wright Corporation. This system consisted of control of air into three banks of the 20 isolators, the flow to each bank determined by demand of a corresponding

height-sensor/flow-regulator valve. The air lines for control are 1/4" dia. polyflow tubing; there are 3/8" globe valves and 1/2" dia. tubing for fast fill to near 'floatation' pressures. This "passive" system, still used as a back-up configuration, maintained the Iso-pad, in a floated mode, parallel to the base slab beneath it. The average operating pressure of the 20 pneumatic isolators is 80 psig. The initial installation was on Barry Controls Job #81F-85279, specification #53-08 titled "Vibration Isolation and Leveling System," and Air Force Academy contract #DA-25-066-Eng-14809. In March 1968, Weston Geophysical Research, Inc. conducted transmissibility performance tests, which are covered below.

4. PASSIVE PERFORMANCE

A soft-sprung passive isolation system does an excellent job of eliminating ground motion of the base slab at frequencies well above the suspension natural frequency. The amplitude attenuation behaves essentially as a second order low-pass filter. Transmissibility at low frequency is 1. The price that must be paid for achieving this isolation from base motion, however, is a high susceptibility to disturbance forces on the platform itself. The transmissibility of force disturbances at low frequency is equal to 1/K, where K is the stiffness of the supporting springs. Since $\omega_N = [K/M]^{\frac{1}{2}}$, lowering the platform natural frequency increases the platform sensitivity to force disturbances by $1/\omega^2$. The desired natural frequency of the passive isolation system then amounts to a trade-off between the amount of isolation against base motion versus force disturbances that is desired.

The choice of a soft-sprung supporting structure or a rigid ground coupling depends to a great extent on the application. For many

experiments, where high freuency accelerations can excite natural frequencies in the test device, the low-natural-frequency, passive system is to be preferred. In this case, the low frequency motions of the platform are of little importance since they do not impart any appreciable acceleration to the item under evaluation. In the case of inertial component testing, however, these small-amplitude, low-frequency motions are intolerable. In gyro testing, the tilt orientation angles and angular rates are of greatest importance, while the tilt angles and linear accelerations are of greatest importance in accelerometer testing.

The Iso-pad has a spring stiffness K = 580,000 (tilt) lbs./ft. and natural frequencies of about 2 Hz in vertical and translational and 1 Hz in tilts and azimuth. For this system, a motion sensitivity of approximately 20 micro-inches/lb. results. If, during testing operations, no personnel activity occurs on or around the isolation platform on which the test table is mounted, the largest disturbance forces to the platform will be caused by low frequency base slab motion and atmospheric pressure changes within the room. The latter disturbance results in a change in buoyance force exerted on the platform. Typically, peak deflections from level would be about 0.1 arcseconds at short periods, and a low frequency (mostly 24 hour period) base slab motion of 2 arcseconds. There is a significant reduction in vibration levels above 3-5 Hz. This is shown in Figure 3, which is the vertical transmissibility as meaured by Weston Geophysical Research in March 1968.

In similar tests of more recent vintage (November 1979), it was found that coherence in a transmissibility measurement was poor over most of the region of interest, due to the non-random nature of the naturally occurring excitation. However, the power spectra of Iso-pad vibration is

useful for observing the high frequency roll-off as well as resultant peaks due to high incident peaks in this environment (Figure 4). Theoretical roll-off of the 2 pole system is 40 db/dec (Figure 5).

5. ACTIVE CONTROL APPROACH

The main deficiencies noted in the performance of the passive Iso-pad are the following:

1. The 'level' of the passive Iso-pad is controlled to be parallel to the base floor, and not with respect to the gravitational vector as is desired for tests of inertial sensors.

2. There is no vibration reduction in the frequency band from the pneumatic activator maximum frequency, about 0.1 Hz, and the natural spring/mass frequency, 1 Hz.

3. The vibration reduction of 12 db/octave roll-off from the natural frequency, leaves an unacceptable large vibration up to about 20 Hz. That is, the 10^{-7}g level vibration of the passive Iso-pad is still excessive for tests of the latest AF inertial navigation instrument requirements.

4. The pneumatic damping of natural frequency motions of the passive Iso-pad is inadequate, and as a result, motion at 1-2 Hz is far in excess of base motion.

The performance of the passive Iso-pad included deficiencies of 3 arcsecond tilts at short periods (about 3-5 minutes) and 2 arcsecond tilts at a 24 hour period. Initial objectives of an active tilt control were set at 0.1 arcsecond maximum deviation. However, with the development of a new generation of inertial guidance components came a greater concern for the influence of erroneous base motion inputs during the evaluation of these devices. Small angular rate deviations on the order of 1 arcsecond

per day or .001 arcsecond per minute will generate a significant error in the performance of one of these gyroscopes. A tilt of the base by as little as .01 arcsecond will generate a significant error in the performance measurement of one of these accelerometers.[1] Therefore, the aim of 0.1 arcsecond was established more from a practical viewpoint than from the need which would be 2 orders of magnitude more difficult.

The objective 0.1 arc sec tilt stability was obtained rather quickly through incorporation of two improvements. The first improvement was straightforward after correlating short period tilt deviations to air supply pressure fluctuations. Improved air pressure regulation by use of a better and second stage of control to about $\pm$ .001 psi provided a satisfactory solution.

The long period tilt was, as previously mentioned, due to use of sensor controls ("height sensors") which are referenced to the base floor. Solar heating of the building and surrounding area is the primary cause of the 2 arcsecond tilts of the base flow. As a cadet project, the feasibility was shown of controlling one axis of Iso-pad level to a reference tiltmeter. Tilt was corrected by changing air pressure in one bank of isolators to maintain the reference tiltmeter at null well within the 0.1 arcsecond objective.

At completion of the cadet project, a harder look was taken at establishing objectives meaningful to future AF test requirements of new motion sensing instruments. The key instruments for future inertial navigation

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[1]Draper, C. S., "Background for Specification, Engineering and Operational Realization of Inertial Sensors to Meet the Requirements of High Quality Control, Navigation and Guidance Systems Adaptable to Marine, Aeronautical and Astronautical Vehicles of all Kinds," MIT Draper Laboratory Report R-623, September 1968.

systems were under development at the Charles Stark Draper Laboratory, Inc. To quote from a 1975 CSDL report,[2]

> The resolution of these new instruments is expected to be so fine that instrument errors and uncertainties must be modeled and verified in order to establish the sources of instrument noise....the following assumptions will be made for performance goals of the next generation of instruments:
>
> (1) Angular motion uncertainty - 10^{-3} meru
>
> (2) Linear motion uncertainty - 10^{-9}g
>
> (3) Measurement bandwidth - 10^{-7}Hz to 10^{-2}Hz.

It will be noted that the Iso-pad active control stability objectives closely parallel these performance goals, and <u>are still not significantly better as would be desired in the test system</u>.

5.1 Sensor Selection

In order to sense the motion of the platform and separate all six degrees-of-freedom in the frequency band of interest (0-10 Hz), a combination of sensing devices is required. For the very low frequency rotations (0-0.1 Hz), a high quality, two-axis tiltmeter is used. The azimuth orientation angle could be measured with a four-position gyro-compassing system with considerably less accuracy than the tiltmeters. However, it would provide a continuous automatic azimuth determination update every four minutes. This azimuth control has not been incorporated in the Iso-pad. No provision is made to measure the low frequency (0-0.1 Hz) translational motions, except for the vertical motion with respect to the base slab. This is measured with a resolution of about 1 microinch by means of a linear variable differential transformer (LVDT) sensor. Since

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[2]AIAA Paper 75-1066, August 1975, "Geokinetics Considerations for Advanced Testing of Gyros and Accelerometers," by R. DiPaola, C. R. Kochakian, and K. Tsutsumi.

neither gyros nor accelerometers are sensitive to this low frequency, low amplitude linear motion, it is of no consequence.

The higher frequency motions (0.1-20 Hz) of the platform are sensed by an array of short-period, matched seismometers. These are positioned on the platform as shown in Figure 6. The output of each seismometer can be represented to first order as follows:

$$V_1 = \ddot{z} + \dot{w}_x d$$

$$V_2 = \ddot{z} - \dot{w}_x d$$

$$V_3 = \ddot{z} - \dot{w}_y d$$

$$V_4 = \ddot{z} + \dot{w}_y d$$

$$H_1 = \ddot{x} + \dot{w}_z d + \dot{w}_y h + \theta_y g$$

$$H_2 = -\ddot{y} + \dot{w}_z d + \dot{w}_x h - \theta_x g$$

$$H_3 = -\ddot{x} + \dot{w}_z d - \dot{w}_g h - \theta_y g$$

$$H_4 = \ddot{y} + \dot{w}_z d - \dot{w}_x h + \theta_x g$$

From the above equations, all six degrees-of-freedom of platform motion can be determined.

$$\ddot{z} = \frac{1}{4}(V_1 + V_2 + V_3 + V_4)$$

$$\dot{w}_x = \frac{V_1 - V_2}{2d}$$

$$\dot{w}_y = \frac{V_4 - V_3}{2d}$$

$$\dot{w}_z = \frac{1}{4}(H_1 + H_2 + H_3 + H_4)$$

$$\ddot{x} = \frac{H_1 - H_3}{2} - \left(\frac{V_4 - V_3}{2d}\right) h - \frac{g}{2d} \iint (V_4 - V_3) dt^2$$

$$\ddot{y} = \frac{H_4 - H_2}{2} + \left(\frac{V_1 - V_2}{2d}\right) h - \frac{g}{2d} \iint (V_1 - V_2) dt^2$$

Instruments surveys were conducted toward selection of tiltmeters, LVDT, and seismometers. Competitive procurement resulted in selection of a Hughes tiltmeter, essentially a modified model TM-3. Tentatively, a low-cost, EV-22 Electrotech geophone was selected as the basic seismometer. The feasibility of matching seismometers and differencing their outputs to obtain angular motion was a successful cadet research project. The EV-22 seismometer has a natural frequency of 7.5 Hz, and the roll-off toward D.C. results in poor signal/noise below about 2 Hz. Use of longer period seismometers toward a usable 0.1 Hz lower limit resulted in final selection of Teledyne vertical SL210 and horizontal Geospace HS-10 seismometers.

5.2 Control Actuators

In order to remove the effects of base motion and force disturbances on the platform, a means of applying a controlled force to the platform is required. This has been accomplished with two separate systems. First, the pressure in the supporting air cylinders themselves is varied in order to remove the low frequency transients (below 1 Hz). Figure 7 depicts the main components used in this system. A push-pull arrangement is used in order to keep the applied rotations about the center of gravity of the platform. In addition, the use of two electric-to-pressure transducers, regulators, and boosters increases the amount of air that can be exchanged, and thus increases the speed of its response.

Pneumatic control components selected, all of which are manufactured by the Moore Products Company, were the following: electric-to-pneumatic transducer - Model 7712 Millivolt Converter; partial supported regulator - Model 40A Nullmatic Pressure Regulator; and air flow booster - Model 61H Booster Relay. Five sets of pneumatic controls are required, 1 set each for the pair of isolators at each cardinal location, and 1 set for height control. The height is controlled at a much slower rate, therefore an air flow booster is not used on the height channel.

The applied force to the Iso-pad in the frequency band above useful pneumatic control, 0.1 Hz, is provided by Model 411 electromagnetic shakers made by Ling Electronics Inc. These shakers are capable of 13 lb. thrust without forced air cooling. Eight shakers are required: the four vertical are located at cardinal points, and the four horizontal are located at the corners of the Iso-pad. The vertical shakers are mounted on the seismic mass, the horizontal are mounted on building support columns (see Figure 2). Mechanical fuse coupling from shakers to the Iso-pad is provided to protect the shakers in the event of excessive Iso-pad translation.

6. ACTIVE CONTROL OPERATION

The objectives of the active stabilization are threefold·

1. Suppression of six-degree-of-freedom angular and linear movements of the block under the influence of disturbance torques and forces. These disturbances are typically caused by floor/wall vibrations; standing air waves in the inner laboratory room; other pressure variations due to doors, air conditioning, etc.; coupled base motion; and limited personnel activity (e.g., adjusting test equipment).

2. Provisions for a seismic motion simulation capability by applying known error signals as a reference into the control loops.

3. To relate the Iso-pad orientation to inertial, not base floor, references.

For suppression of disturbance induced motion, the great inertia of the block itself provides a high degree of passive isolation for frequencies above 20 Hz. Based on this and the anticipated test requirements, the active stabilization and control system is designed to be effective up to approximately 20 Hz. The excitation function, with some exceptions noted later, is not limited.

In order to remove the effects on base motion and force disturbances on the platform, a means of applying a controlled force to the platform is required. This has been accomplished with two separate systems. First, the air pressure in the supporting pneumatic actuators is varied in order to remove the low frequency transients (below 0.1 Hz). The low frequency angular motion about the horizontal axes is measured by the Hughes TM-3 tiltmeter (0.001 arc sec resolution). At low frequency the other four degrees-of-freedom, x, y, and z translation and azimuth, continue to be "floor-based" references until development of suitable inertial sensors.

Secondly, motion above 0.1 Hz is sensed inertially by seismometers; and the motion in all six degrees-of-freedom is obtained. The three translation motions are obtained as an average of two horizontal or four vertical siesmometer signals. The three angular motions are obtained as differences of pairs of matched seismometers. The angular resolution is inversely proportional to the separation of the two seismometers; as a result, the resolution of a difference signal from the two SL210's at

opposite sides of the pad (i.e., a 25 ft. "leg") is better than the best available angular accelerometer.

The six-degrees of high frequency motion signals, $f > 0.1$ Hz, are amplified, conditioned, and applied as correction forces to the Iso-pad by means of electromagnetic shakers. The eight shakers in use, four vertical and four horizontal, are Ling model 411 units capable of about 13 pounds thrust in the non-force-air cooling mode.

6.1 System Operation

The twenty air tanks are connected so the pressure of outside pairs (eight total) may be varied to tiltmeter command. The remaining "inside" tanks are inner-connected and are pressure controlled within a narrow pressure range to maintain the Iso-pad height to within a few micro-inches. The outside, "tilt", tanks are controlled in pairs over a wider range, 72 ± 7 psig, to correct tilt errors. Figure 8 depicts, for one angular and one linear degrees-of-freedom, the main components used in the vertical system. At null conditions, the pneumatic actuators apply the correct lift to maintain the Iso-pad at 0.5 inch above the seismic mass in a level condition. If a height error develops, air is input or exhausted to the 12 inside tanks until the null is restored. If a tilt error develops, the amplified TM-3 signal is applied through electric-to-pneumatic transducer, partial supported resulator, and flow booster to the pairs of "outside" tanks to input air into the low side and exhaust air from the high side. This push/pull arrangement is used in order to apply rotational correction with a minimum effect on the linear height control loop.

Sum (Σ) and difference (Δ) signals are formed from the seismometer outputs, and applied to the shakers as shown in Figure 8. The sum signal corresponds to a vertical motion, and difference signal corresponds to an

angular motion of the Iso-pad in the frequency range $0.1 < f < 20$ Hz. The shakers apply appropriate forces to counteract the sensed high frequency motion.

This description illustrates the principles of system operation. One could picture Figure 8 as an E-W angular or a N-S angular servo illustration. In practice, the vertical servo loop final configuration uses a single vertical seismometers located at the center, over the c.g., and the vertical correction forces are applied by all four vertical shakers. The single center seismometer is useful in matching the vertical servo loops.

The high frequency servos for horizontal forces operates in a manner similar to the vertical controls described above. The three degrees-of-freedom, N-S and E-W translation and azimuth rotation, are sensed by four horizontal seismometers and controlled by four horizontal shakers within a frequency range $0.1 < f < 20$ Hz (see Figure 9). The shakers are based on four columns adjacent to the Iso-pad, and forces are applied to the Iso-pad in the c.g. plane. Low frequency actuators and sensors have been considered but none are in use pending availability of practical DC-0.1 Hz horizontal, inertial motion sensors.

6.2 Low Frequency Tilt Loop

Figure 10 shows a block diagram of the tiltmeter/pneumatic control loop. This loop is designed for controlling the very low frequency and steady state tilt of the isolation block. The following is a description of the dynamics of the different blocks in the diagram.

Tiltmeter, T(s)

A theoretical analysis of the Hughes TM-3 servoed bubble tiltmeter dynamics gives the following transfer function referred to an angular input:

$$T(s) = \frac{K_T\left(1 - s^2\,\frac{a}{g}\right)}{\frac{s^2}{\omega_T^{\,2}} + \frac{2\zeta_T}{\omega_T} + 1}$$

where: s = $j\omega$ is the complex frequency

K_T = constant scale factor (volt/rad)

a = 1.5m is tiltmeter offset above the axis of rotation (See Figure 2)

g = 9.8 m/sec^2

ω_T = 6.3 rad/sec

ζ_T = 0.6

ω_T and ζ_T are natural frequency and damping constant dependent on the dynamics of the bubble restoring servo loop. The given values apply to the actual TM-3 instrument at normal setting. However, measurements of the response show a roll-off above 1 Hz which must be due to the bubble fluid dynamics that were neglected when deriving the theoretical transfer function. By experimental curve fitting, one can obtain a good match with measured response by adding one extra pole. Hence the transfer function of the tiltmeter is

$$T(s) = \frac{K_T\left(1 - s^2\,\frac{a}{g}\right)}{\left(\frac{s^2}{\omega_T^{\,2}} + \frac{2\zeta_T}{\omega_T} + 1\right)(1 + T_T s)}$$

where $T_T \simeq 0.2$ sec.

Isolation Block, B(s)

The isolation block dynamics are represented by a second order spring-mass mechanical system, and the transfer function from torque input to angular displacement output is:

$$B(s) = \frac{K_B}{\frac{s^2}{\omega_B^2} + \frac{2\zeta_B}{\omega_B} s + 1}$$

where: K_B is the spring constant (rad/Nm)

$\omega_B = 7$ rad/sec

$\zeta_B = 0.05$

Pneumatics, P(s)

Due to air flow restrictions and large cylinder volumes, the transfer function from voltage input to torque output is approximately a simple pole at low frequency:

$$P(s) = \frac{K_N}{1 + T_N s}$$

where: K_N is the transfer constant (Nm/Volt)

$T_N \simeq 20$ sec

Compensator $C_1(s)$

To restore accurate steady state levels at heavy torque loadings (test tables, instruments), the compensator must include an integrator. Taking stability considerations into account, the compensator chosen is:

$$C_1(s) = \frac{K_1(1 + T_1 s)}{s}$$

where: K_1 is the gain constant

$T_1 = 20 \simeq T_N$

6.3 Mechanical Resonances

Control loop dynamic problems caused by sharp mechanical resonances must be taken into account. The resonances can occur in the sensor, in the actuator linkage, or in the isolation block itself. It will always be

wise to put a multipole low pass filter in the loop to suppress resonance peaks. But the cut-off frequency of the filter must be at least 4 to 5 times the control band upper limit in order not to give significant phase lag contribution at the crossover frequency. Therefore, the low pass filter will not attenuate resonance peaks that are 2 to 3 times above the control band limit. A few of these resonances can conveniently be attenuated by notch filters. Also, the large phase lag associated with damping or mechanical absorption can occasionally be usefully compensated with a peak filter.

In the actual control system, the largest structural resonances are the lower resonance modes of the isolation block. Figure 12 shows four first order resonance modes that must be considered. The 59 Hz mode affects the design of the vertical control loop. The 65 and 67 Hz modes affect the design of the angular control loops for the horizontal axes.

Figure 13 shows the impact of the 65 Hz resonance mode upon the design of the high frequency angular control loop for the correspondent horizontal axis. The figure shows how the resonance appears in the open loop transfer function. This open loop transfer function must be modified by a notch filter and a low pass filter to suppress the resonance peak.

The solid curves of Figure 13 show how the closed loop will be unstable at 65 Hz according to the Nyquist stability criterion. The notch filter has an insignificant phase lag contribution at the loop crossover frequency of 20 hz, but it effectively attenuates the resonance peak at 65 Hz. This is shown by the broken line in Figure 13.

There is a lower frequency resonance in a sensor which presents stabilization difficulty. This is a resonance in the proof-mass support spring in the SL210 long period seismometer at 35 Hz. This support spring is

about 1.5 in. diameter and 2.5 in. long. Attempts were made to dampen this spring resonance by several types of viscoelastic damping materials and silicone oil bath. The most effective treatment was by oil bath damping, but the method does not lend itself to long term use. The manufacturer, Teledyne/Geotech Inc., is also working on this 35 Hz resonance problem.

There are numerous unidentified higher frequency resonances associated with one or more of the 6 degrees-of-freedom. These resonances start at 85 Hz and range into the kilohertz range associated with shaker brackets, mounting plates, coupling rods, and the Iso-pad itself.

6.4 Seismometer Matching

A significant effort was made to obtain 'matched' seismometers to enable a sum and difference of signals to be usable for linear and angular motion measurements. Approximately identical scale factors on instrument pairs were selected; further matching was performed by adjusting external resistance damping and gain. These matched sets were used in most of the earlier Iso-pad servo development, and in making absolute motion measurements for vibration source identification (to be discussed later). However, the angular motion sensing and application of correction torques about the center of gravity, c.g., involves other parameters, e.g., shaker scale factors, physical location of sensors and shakers relative to the c.g., and gain of all non-common electronics such as power amplifiers.

With reference to Figure 8, the final 'matching' for angular servos was performed as follows: A vertical seismometer is placed over the Iso-pad c.g. (where Figure 8 shows the tiltmeter); the Iso-pad is excited in the angular mode with a sine wave signal to the two shaker, power amplifiers; and the vertical seismometer is monitored for sensed vertical

motion, which would indicate an unbalance in effective forces of the two shakers, with a consequent vertical component. The shaker amplifier gains are adjusted to null the vertical seismometer output. Note that any significant mismatch in the seismometers will result in an error in the vertical servo: however, stability of the angular servo is the more important to gyro tests.

6.5 High Frequency Loops

Figure 11 shows the open loop frequency response of the E-W angular loop as typical of the six high frequency control loops.

The major problem which prohibits significant gain increases are resonant poles within the Iso-pad structure, instruments, shakers, and associated mounting hardware. These higher frequency resonances, all over 35 Hz, were investigated and attempts made to alleviate some of the identified modes of vibration. Figure 14 is a schematic of the form of amplifier/compensator electronics for the six control loops. Input resistors, R_d, serve as both seismometer damping and matching, since R_{d11} plus R_{d12} is a resistance in parallel with the seismometer coil and R_{d11} is a variable in the amplifier gain applicable to seismometer #1. Circuit features include nOrmal lead and lag compensation, plus notch and peak compensators to effect stabilization at the more extreme mechanical resonances. Loop gains were adjusted to below optimum performance to allow for significant coupling between loops and to put the Iso-pad in a high reliability mode at the conclusion of the research efforts.

7. CONTROLLED EXCITATION

7.1 Method

One of the most important uses of an active-control Iso-pad has been for imposition of known excitations to test specimens. For example,

during a gyro test, a given frequency of angular vibration could be imposed about an E-W axis and the effect measured on the gyro performance. All motion in six degrees-of-freedom at one test site could be measured, taped, and the playback used as excitation to the six channels of Iso-pad active control servos. The technique (Figure 15) is straightforward, and has been used in instrument comparisons. Excitation signals, from function generator, random noise generators (RNG), or tape are imposed on the tilt servo for low frequency excitation and the seismometer/shaker servo for high frequency excitation.

Two other forms of excitation used occasionally are step-inputs to vertical shaker channels by means of weight lifts on the pad and the use of a "floating" shaker, positioned on the Iso-pad without coupling to ground, but loaded with a 2 to 3 pound weight. The latter technique is sufficient to excite some resonant modes of vibration in the Iso-pad and test specimens.

7.2 Small Excitation Test Example

Use of the Iso-pad in the excitation mode has thus far been limited to extremely small motions as appropriate for comparison of precision instruments. The data in Figure 16 is a comparison of five instruments with milliarc second resolution capability. Here, with the Iso-pad active, a sine wave excitation is imposed in the pneumatic (low frequency) controls to effect a N-S angular motion of 0.005 arcseconds at 0.15 Hz. It may be seen from the example that the Iso-pad provides adequate background stability for making such low level measurements. The original purpose of the test, to prove milliarc second resolutions of these sensors, was accomplished. The "absolute" magnitude of the excitation is an extrapolation of the scale factor, angle/volts, measured at a larger excitation by

the appropriate calibrated angular sensor. The large excitation is then reduced to the desired level by means of a voltage divider; the assumption is made that the Iso-pad scale factor of response to excitation signal remains constant as the level of excitation is reduced by means of the divider. This technique was tested and the scale factor remained constant for angles of the order of 0.1 to 20 arc seconds. In this example, the use of a calibrated TM-3 tiltmeter was appropriate to the 0.15 Hz angular excitation.

7.3 High Frequency Capability

The limits on pad motion as a high frequency exciter are set by the shaker capcity. As it stands now, these capacities are limited to about ± 13 lb. rms force. These values could be doubled if air cooling is supplied the model 411 shakers; and of course, if a project warranted the expense, larger shakers could be installed.

There are resonances in the Iso-pad which are outside of the servo control range of DC-20 Hz. Tests performed to determine Iso-pad maximum capabilities revealed that these resonances were excited by subharmonics within the control range. For example, the 65 and 67 Hz resonances due to Iso-pad bending are excited by 13 and 13.4 Hz, the fifth subharmonic angular excitation respectively. This effect was measured in the servo-off, or passive, mode since modification work was in progress. One would expect this to be greatly reduced when servos are activated. The subharmonic excitation effect is generally not expected to be a significant test limitation for most test specimens.

7.4 Low Frequency Capability

The limits on pad motion as a low frequency (LF) exciter are determined by the rate that the pneumatic actuator pressure can be changed.

The air booster, Moore part 61H, provides a significant increase in rate of air flow from the electric-to-pneumatic transducers; but due to the large actuator volume, motion above 1 Hz, as a result of LF excitation, is rather insignificant.

The motion capability increases rapidly (approximately 20 db/decade) with decreasing frequency. At near DC the tilt angle is a more meaningful limit. The diaphragm positions of the pneumatic isolators are capable of at least $\pm 1/4$ in. variations. Safety devices prevent extensions of greater amplitude; this places a limit on the maximum tilt at about 5.7 arcminutes p-p, the maximum tilt at DC.

7.5 Load Weight Limits

The maximum weight of a test specimen on the Iso-pad (i.e., DC capability) is dependent on the test location and whether changes to the pneumatic actuator set-up are warranted. For a test pier location at a cardinal point, the present weight limit is about 5,000 lbs. A pair of pneumatic actuators would operate at about 90 psig vs the nominal 80 psig. And, considering the small change in Iso-pad inertia that a 5,000 lb. load would effect, the motion characterization would be relatively unaffected. But there are possibilities of accommodating a larger load than 5,000 lb. For example, it is possible to use the center pier for a test so that the load is shared by all actuators; it may be practical to increase the supply pressure; and it is possible to rearrange the actuators to better support a side or corner load.

7.6 Excitation Limits

The objectives were met of obtaining Iso-pad motion excitation limits for high-frequency (HF) angular and translation modes, and the low-frequency (LF) tilt modes. As discussed above, there are presently no

provisions for LF translation and azimuth modes, but it is possible to obtain LF vertical excitation motion. Typical frequency response plots were covered in the paper to ISA in 1979.[3] Table I shows a summary of the excitation limits.

TABLE 1
Maximum Excitation at Typical Frequencies

Mode	Motion x 10	Frequency Hz
N-S "Tilt" Axis (HF)	1350 rad/sec^2	16
E-W "Tilt" Axis (HF)	1380 rad/sec^2	16
Vertical (HF)	3800 g	16
Azimuth (HF)	1640 rad/sec^2	16
N-S Translation (HF)	2400 g	16
E-W Translation (HF)	2400 g	16
N-S Tilt (LF)	64 rad/sec^2	0.27
E-W Tilt (LF)	64 rad/sec^2	0.27

8. STABILITY PERFORMANCE

8.1 Background

The Iso-pad active-control system has recently undergone an improvement program to incorporate long period SL210/SL220 seismometers. The following data is as a result of current system status. The final instruments complement was: 4 vertical SL210's, 4 horizontal HS-10's, a single vertical HS-10, and the 2-axis TM-3 tiltmeter. It was not possible to improve system performance with the SL220 horizontal seismometer due to mechanical resonances. The SL210 vertical seismometers are used at servo

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[3]ISA paper, "A Sub-Seismic Test Platform as a Motion Exciter," by Bill J. Simmons, FJSRL, May 1979.

gains which do not cause the 35 Hz sensor resonance to be unstable. The lower frequency (0.1) utility of the vertical sensors for angular control of tilt axes was very desirable.

Tilt augmentation, a feature in which an additional loop is provided by summing the tiltmeter output into the shaker actuators, is used. This input, with proper compensation, improves performance of the N-S and E-W angular loops in the 0.002 to 0.15 Hz frequency band. Also, with the requirement for lower frequency response, a long-period auto-bias correction circuit was incorporated in the angular servo electronics.

8.2 Active Performance

The closed loop frequency response of the high frequency angular control loop is shown in Figure 17 at optimum gain. One can see that the system gives good attenuation at all frequencies. The angular motion sensitivity to disturbance torques is attenuated by more than 20 db over the DC-10 Hz control bandwidth when referred to the passive isolation block.

The plots of final performance shown in the following are taken using the modified, high reliability, electronics and are shown as auto power spectra (APS) of 'residual' motion in each degree-of-freedom. Figure 18 shows the performance of the E-W angular degree-of-freedom. The APS of the motion sensed as the difference of the East and West vertical SL210 seismometer-pair, with the servo 'OFF', is shown in Figure 18a. When the servos are actuated, the residual motion is as shown in Figure 18b. The rms of the residual motion as angular velocity, Ω rms, is proportional to the square root of the integral of the APS over the frequency band of interest. The rms-velocity, rms $\Omega = \frac{1}{k}\,(2 \times \int APS)^{1/2}$ where k is the seismometer-pair angular scale factor x amplifier gain. This proportion-

ality constant, k_i, will generally be different for each degree-of-freedom, since each servo axis may involve different seismometers and different amplifier gain. Taking the E-W angular servo as typical, the calculation of k, and comparison of 'OFF' vs 'ON' motion are as follows:

k = scale factor x amplifier gain in volt-sec/radian

The linear scale factor of E-W angular seismometers, SL210's = 2.3 volt/ips

The basic angular scale factor of the pair is 13800 volt-sec/radian

The gain for measurement of Figure 18 = 10K

Thus, $k_{E-W \measuredangle} = 13.8 \times 10^7$ volt-sec/radian

From Figure 18 the integrals of the motion APS in the frequency band DC to 20 Hz are 0.18 $volt^2/Hz$, open loop, and 0.002 $volt^2/Hz$ with servo closed. As an indication of active control effectiveness or stability performance as superior to the passive Iso-pad is a comparison of rms-motion in the two.

$$\text{Stability improvement} = \left(\frac{0.18}{0.002}\right)^{\frac{1}{2}} = \sqrt{90} = 9.5$$

Thus the motion stability of the E-W angular degree-of-freedom is improved by a factor of x90 on a rms-signal power, and x9.5 on a rms-velocity basis.

The base floor seismic motion was not measured during the test, and does vary about 5:1 in time with weather, earth seismivity patterns, and cultural effects; and of course can be much larger in the event of a large earthquake. Be that as it may, the absolute values of motion on the Iso-pad with servos 'ON' in the E-W angular degree-of-freedom at the time of this test can be determined as follows:

$$\text{rms} - \Omega\Big|_{0}^{20} = \frac{1}{k_{E-W \measuredangle}} (2 \times \int APS)^{\frac{1}{2}} = 4.6 \times 10^{-10} \text{ radian/sec rms}$$

It is sometimes convenient to express this residual motion as a linear motion, and in the acceleration dimension 'g'. The equivalent vertical motion at the edge, due only to the angular vibration on the 300 inch Iso-pad, is a V_{rms} of 7×10^{-8} inch per second. To determine acceleration from A = V, it would be necessary to identify the velocity with a frequency. A course approximation can be made by using the rms-velocity and assuming it a pure sinusoidal motion at 3 Hz, about mean value on the integral plot. The acceleration calculated from such an approximation is 1.1×10^{-7} ft/sec^2, or 3.4×10^{-9} g.

The APS and integral of closed loop stability performance of other degrees-of-freedom are shown in Figures 19 through 23.

8.3 Impulse Performance

Another performance criteria is the measure of offset and recovery to each degree-of-freedom to an impulse such as might occur from personnel activity. In practice, it is not expected that personnel traffic would be permitted during the use of the Iso-pad to conduct a very critical test. However, the reaction is shown here to impulses by weight lift, door closures, and personnel traffic. The servo is set at optimum gains, and results are shown only for the N-S angular degree-of-freedom, as an example. Figure 24 shows the angular response of the isolation block to 60 lb-ft step torque input. This was obtained by lifting a 5 lb. lead mass from one end of the seismic block. The angular signals shown were taken from the output of the tiltmeter under the three conditions: passive Iso-pad, low frequency tilt loop ON, and both low and high

frequency angular loops ON. These responses were measured with the horizontal control loops inactivated to show the cross coupling of linear motion into the tiltmeter. The cross coupling appears in Figure 24 as a ripple at 2 Hz which is the natural frequency of N-S translation.

Figure 25 shows the angular response to ambient disturbances including a man walking on the false floor around the block and a door slamming in an adjacent room. The measurement bandwidth is from 0.2 Hz to 60 Hz. One can see that the high frequency control loop reduces the angular motion from about 0.01 arc second to below 0.001 arc second in that frequency band.

9. RELATED TASK HIGHLIGHTS

As previously noted, there have been many tasks which were Iso-pad related by way of being part of the Iso-pad development or other work dependent on the Iso-pad low-vibration environment. In the following, there's no attempt at detailed description, but to provide sufficient information to describe the Iso-pad association.

9.1 Seismometer Compensation

Precise measurement of geokinetic disturbances were required to monitor and control the Iso-pad. Low-cost compact seismometers were compensated to obtain flat frequency response characteristics over a broad range. Using random-noise excitation of a bridge circuit, damping and electrical compensation values were determined which extend the useful bandwidth almost a decade below the seismometer natural frequency. The concept was initially proven feasible as a cadet project using HS-10 seismometers.

9.2 Seismometer Matching

A survey of available instruments as suitable sensors for active control to 10^{-8}g revealed no usable, high-frequency angular motion sensor. The investigation of matching seismometers, and measuring angular velocity by differencing the outputs of two of the linear velocity sensors, was proven feasible.

9.3 Instrument Calibration

Many instrument studies have been performed where the motion stability of the Iso-pad was necessary to the task of separating signal from noise. The first of these was to 'calibrate' seismometers by comparison to a known reference on the motion excited Iso-pad and on a Hughes LRB-12 tilt table mounted on the Iso-pad. Reference seismometers were calibrated by Newark AFS, Ohio.

9.4 Portable Seismic Monitor

The Portable Seismic Monitor (PSM) was developed as a solution to the many motion/vibration measurement tasks associated with an inertial instrument test laboratory. Generally, both linear and angular motions of test equipment and facility surfaces must be measured and evaluated. Also, it is often necessary to make measurements at locations of 100 feet or more from the laboratory power supplies and analysis test equipment. This necessitates the transmission of very low-level signals over long lead lengths. With geophones as sensors, an electronics carrying-case package was designed which includes four channels of high gain amplifier compensation networks, a power supply, an indicator, and auxiliary output provisions. Similar requirements at other guidance test laboratories, particularly the Central Inertial Guidance Test Facility (CIGTF) at Holloman AFB, resulted in fabrication of a 2nd PSM to FJSRL drawings by HAFB.

9.5 Modeling of a Seismic Isolation Block

A model was developed for the Iso-pad which describes the motion of the block and the effects of pad unbalance, pneumatic cylinder damping, cylinder spacing and spring points of action on the natural frequencies, damping ratios and cross coupling of the modes of vibration. The Iso-pad and its suspension was considered as a holonomic linear mechanical system with six degrees-of-freedom which vibrate about a stable equilibrium position. The motion, described by six generalized displacement equations, was solved for the Iso-pad, and results compared (favorably) to experimental test data. The methodology is generally applicable to any seismic isolation block.

9.6 Digital Control Techniques

From the beginning, the problem of interest has been that of designing and implementing controllers to provide the desired degree of isolation (angular position within $\pm$ 1.0 x 10^{-3} arcsecond and angular rate within $\pm$ 1.667 x 10^{-5} arcseconds/second). Early investigations and attempts at stabilizing the platform were primarily analog control systems. Starting in 1973 there were studies both at the Air Force Institute of Technology (AFIT) and by a contractor to FJSRL (Kappa Systems, Inc.) on potential advantage of Iso-pad active control using digital techniques.

In 1973 AFIT developed a program, and the FJSRL HP 2114B computer was utilized to activate a 1-axis tilt control loop on the Iso-pad using various finite impulse and infinite impulse response filters. Periodically, enlargement of the task toward higher performance and multi-axis control has been a subject for AFIT graduate student theses.

Digital control was considered because it is potentially less affected by noise and other disturbances than analog systems, permits the use of

sensitive control elements with relatively low energy signals, and may be given phase characteristics that cannot be duplicated by an analog system. Digital control is more flexible than analog control because changes in sensors or actuators can often be incorporated with only software modifications. An additional benefit of digital controllers is their adaptability to the solution of stochastic optimal estimation and control. A 1979 AFIT study simulated the application of linear stochastic optimal estimation and control to a simplified Iso-pad model. The system was modeled as a linear system with stochastic disturbances. A forced separation concept was employed in order to independently investigate the effect of the Kalman filter and the optimal controller. Optimal and suboptimal Kalman filter models were developed and evaluated at physically realizable sampling rates. A general optimal estimation and control algorithm was developed and a proposed sequence of algorithm computations was presented. The results indicated that the optimal estimation and control system was capable of improving the performance of the inertial instrument test platform but not capable of meeting the design specifications for the platform as presently instrumented. The angular position specification can be met based on a sampling rate of 200 Hz and the assumption that the Kalman filter provides estimations that are accurate within the angular position specification.

As presently configured, the platform angular rate uncertainty specification could not be met at any physically realizable sampling rate. The failure to meet this specification was due, primarily, to the fact that there is no direct measurement of platform angular rate.

The AFIT simulation, discussed above, was based on a simplified Iso-pad model which assumed no resonances other than the natural frequencies.

The contractor effort included attempts to effect sharp loop signal filtering to eliminate high frequency resonance in the loop components. Since the lowest frequency mechanical resonance is only an octave higher than the desired control band, the phase lag of the filter was required to be independent (follow) the amplitude roll-off - an impossibility per Bode's theorem. No advantage was found of digital over analog techniques applicable to this problem.

9.7 Cadet/New Lieutenant Projects

A number of Iso-pad related projects have been performed primarily by cadets and new Lieutenants, when a project of reasonably definitive scope could be defined. The available cadets were students performing a research task and report for senior level classes; the lieutenants were on standby awaiting the start of flight training. These projects included the following examples:

Seismometer compensation for broad band sensor applications (discussed above).

Use of the PSM to study the problem of vibration of components in a holographic set-up.

Use of the PSM to show feasibility of monitoring an astronaut's heart beat from spacecraft vibration.

Set-up on the Iso-pad, of a demonstration test of accuracy improvement from very long-leg mercury tiltmeters. Half of each of two available tiltmeters was used, with flexible tube connecting the mercury septums to form a tiltmeter with 20 ft spacing between septums.

A new concept in tiltmeter design, termed the auto-leveling tiltmeter, was disclosed and tested on the Iso-pad.

The Fast Fourier Analyzer, in use on Iso-pad studies, was used in a speech analysis and synthesis task.

The vibrational analysis of a 'Third Generation' Inertial Test Table, manufactured by Fecker, now Consalvez Goerz Corporation, was performed.

The latter effort addressed the problem of better definition and possible correction of undesirable high frequency vibrations imposed on

the test specimen due to resonances in an Inertial Instrument Test Table. The disturbances are those which will effect results of high speed tests on the newly developed precision inertial grade gyro and accelerometers, and also on medium precision strap-down systems. The typical levels of interest are frequencies from DC to 50 Hz at 10^{-6} to 10^{-9}g. The Iso-pad has the necessary capabilities of exciting a large test table in the frequency range and at the g levels mentioned above. The Laboratory also has a Third Generation Instrument Test Table mounted on the Iso-pad which is a typical specimen for resonant vibration study. Frequency response tests were conducted on the test table, main vibration modes were isolated, and some simple corrective modifications attempted.

The PSM was used to sense motion at several points on the table and on the Iso-pad. The transmissibility and resonant characteristics of the table were obtained. Resonances occur in the table at 22, 31 and 34 Hz. The modes of vibration were identified. The effects on transmissibility of several modifications in structural stress and mounting were determined. For example, the 22 Hz resonance could be changed to 25 Hz by shortening the length of the exposed adjustable base screw.

Many of these test tables are in use by the Air Force, other DOD organizations, and industry, and results were made available to these users.

9.8 Third Generation Gyro (TGG) Tests

At AF-SAMSO designation, a TGG fabricated with specified modifications was allocated to FJSRL. An additional features of the TGG #S-001 includes more thermal monitoring capability. Test equipment, mostly of CSDL fabrication, was obtained, and a joint C. S. Draper Lab/FJSRL research program conducted.

9.9 Angular Motion Sensor (AMS)

Recognizing the possible need for better high-frequency angular motion sensors, a contract was released for development of an AMS. The contractor, Okubo Instruments, performed most of the development tests on site to provide a low motion environment for the experimental sensor. The completed instruments were compared with seismometer-pair and other motion sensors. The sensors were used in one Iso-pad control configuration, and publicly disclosed in AIAA meetings.

9.10 Precision Instrument Comparison

Initially the Iso-pad was used to provide the low motion environment comparing sensitivity and long-term stability of precision tiltmeters and seismometers for possible use as active-control sensors. When the motion excitation capability was incorporated in the Iso-pad system, it became possible to compare a number of motion sensors being considered for various Air Force applications. One such task reported was comparison of performance between several high quality motion sensors.

The instrument parameters of most interest in developing improved test techniques and motion control are threshold sensitivity, stability, signal/noise (s/n), and frequency response. The need for a more stable test base (or pad) is evident when one considers that sensor specifications for threshold sensitivity are orders of magnitude below the nominal motion of a good test pad of seismic-mass design. The latest generation of inertial guidance components, for example, will generate a significant error at angular rate deviations of 0.001 arc sec per minute. In attempts to determine instrument response at 1 Hz, the motion of the test pad must be controlled, or at least known, to about 10^{-5} arc sec. Although this paper was not intended as an instrument survey and evaluation, the rela-

tive capability of several types of sensors used for the various linear and angular motions was shown. Except for test specimens, e.g., the TGG gyro, there was no intent to compare motion sensors other than as required in association with Iso-pad development. The primary goal has been to select sensors with low threshold, usable S/N, long term repeatability, low temperature coefficient, low cross coupling into the sensitive axis, etc., compatible with the Iso-pad stability objectives. Another requirement has been for motion mode measurement in six degrees-of-freedom from DC to a high frequency initially considered to be 100 Hz, and use of sensors in continuous control servos. This test covered comparisons of the following sensors:

Seismometers:
- Electro Tech Labs: EV-22 (Horizontal & Vertical)
- Geo Space Corporation: HS-10 (Horizontal & Vertical)
- Teledyne/Geotech: S-13 (Horizontal & Vertical)

Tiltmeters:
- Hughes Research Lab: TM-3 (2-axis)
- Okubo Instruments: Hg TM
- Teledyne/Geotech: #33520

Angular Accelerometer:
- Okubo Instruments: AMS (Horizontal & Vertical)

Linear Accelerometer:
- DIAX, Inc.: DIAX (Horizontal & Vertical)

Azimuth Angle Sensor:
- Teledyne/Geotech: Azimuth Orientor (non-inertial)

Gyro:
- C. S. Draper Lab: TGG Gyro Serial #SLG-1

The PSD plots, Figure 26, incorporate data on most of the Iso-pad sensor set and the TGG under a N-S angular motion excitation and identical test conditions. This is the same data plot as Figure 16 with one more instrument. Basic test condition were: the Iso-pad N-S and E-W angular servo channels are active; sine wave excitation signal is imposed in the pneu-

matic controls to effect a N-S angular motion of 0.005 arc seconds at 0.15 Hz; and the lab is maintained at "quiet" operational status. All sensors detected the calibration signal; but the AMS was marginal. It is evident that, for some sensors including the TGG, motion of 1 or 2 orders of magnitude smaller would be measurable.

9.11 Flexure Rigidity Sensor

FJSRL developed a flexural rigidity sensor (FRS) that makes it possible to measure dynamic deformations of structures in the presence of large linear vibrations. Such measurements would be used to provide a "spectral signature" of a rigid member under varying load conditions. Changes in the "spectral signature," identified by analysis of the FRS signal, may be an indication of impending structural failure.

9.12 Mercury Level Tilt Sensor

The mercury level tilt sensor was a product of contracted advanced sensor research performed on site. The resulting sensors demonstrated capability of detecting and measuring angular motion in the frequency range of 0.001 Hz to 20 Hz with a sensitivity of 0.001 arcsecond. Several units were completed and are in use at WPAFB and Holloman AFB.

9.13 Angular Accelerometer Schuler Pendulum (AASP)

A single-axis, gyroless, vertical indicating system was designed and built at FJSRL. This system was invented by AF contractor, Dr. Okubo. The AASP was capable of sensing accelerations as small as 10^{-4}g and uses only a compound pendulum and a rotor as its sensing elements, both made with fused quartz suspensions. Input linear accelerations normally causing the pendulum to rotate are sensed by the rotor and proportional signals are fed back to a torquer to maintain the pendulum vertical. An

output signal proportional to the tangential (linear) acceleration is also provided.

Stationary tests were conducted on a small linear shaker mounted on the Iso-pad. Subsequently, the AASP was successfully tested at Holloman AFB. AFOSR has now provided basic development information to industry for possible follow-on development.

9.14 Servo Component Studies

Several types of equipment which have potential for active-control application have been tested using the Iso-pad as a motion exciter. A key problem in active-control system applications is the possible addition of resonances. Such resonances, or poles, add to the difficulty of servo stability solution. The Iso-pad use to obtain the frequency response of motion sensors has been covered. Other test specimens for which the Iso-pad was used as a motion exciter include instrument mounting brackets, instrument cases, shaker coupling components, and small test tables.

9.15 Improvement Concepts

The final performance of the Iso-pad does not meet position and rate criteria in the full frequency band of interest. Additionally, there have been test pad stability requirements identified by Holloman AFB that are more difficult than the Iso-pad objectives. A number of concepts which have potential for improved system performance have been identified. Two concepts identified as part of the past year's completing effort were studied. These were 'position feedback' and 'damping decoupling.'

A small positive gain in stability by use of a 'tiltmeter augmentation' angular position in two of the degrees-of-freedom was identified as early as 1974. This concept was an enhancement on stability of N-S and E-W angular servos. All the high frequency servos are based on velocity

sensors (seismometers). Based on the recognition that the position signal from a velocity sensor at constant amplitude position rolls-off at 20 db/dec, it was proposed that the servo sensor signal be integrated to provide this characteristic. The resulting roll-off in response would circumvent the problem of high frequency resonance. The study showed that it was not possible to provide an integrator at frequency well below the seismometer natural frequency (0.1 Hz) and sustain usable signal levels to the desired 20 Hz upper limit. The tiltmeter augmentation scheme was retained in the two horizontal axis, angular servos.

The 'damping decoupling' concept was also an approach to solving the high frequency resonance problem. Figure 27 shows one of several configurations considered. Here, multi-layer dampers provide a mechanical filtering of high frequency excitation to the Iso-pad. The dampers are a constrained, multi-layer composite of a viscoelastic material, e.g., 0.1 inch DYAD, and .032 inch steel. The shaker bracket is designed so that the forces applied by the shaker through the dampers are in shear for maximum damping and minimum compression. The transfer function of this configuration, see Figure 28, shows a very high gain resonance at 104 Hz. Such a high gain resonance, and its attendant 180° phase change, appear to be due to a spring/mass, K/m, resonance rather than a slowly decaying damping phenomena, and certainly does not mitigate the problem of servo instability due to other resonances. Also it was noted that this damping-decoupling configuration rolls-off toward low frequency, rather than having a flat low frequency response as desired.

Further investigation indicated that the 104 Hz resonance is probably associated with the mounting block (Figure 29) and 'soft' concrete of the Iso-pad. Test of similar configuration on the East shaker bracket showed

a 88 Hz resonance, and the two, as an angular actuator, results in a dual resonance, 360^{o} phase shift system. The spring/mass resonance overrides any effect which would have shown as damping. Therefore, the tests were inconclusive on possible advantage to be gained from damping decoupling. No method was disclosed which tested the damping potential with a configuration free of the mounting-block/Iso-pad K/m resonance.

10. CONCLUSIONS

This report reviews the background analysis and implementation of a practical multi-loop, active servo control system for a passively supported instrument test platform (Iso-pad). Some particular servo control problems due to sensor limitations and seismic block resonances are covered. Performance data for the six degrees-of-freedom have been shown, and significant reductions were made in the sensitivity of the Iso-pad to external disturbances, e.g., base motion. Several examples of the use to which the Iso-pad has been applied during this research task have been briefly described. The following comments apply to the specific objectives on work unit 2304-F2-63, identified early in the report.

10.1 Stability Performance

Six degrees-of-freedom motion stability control have been incorporated through activation of two low-frequency tilt control loops and six high-frequency control loops. Tilt control is of the order of 1 milliarcsecond rms stability at low frequencies. The angular rates of these low frequency tilt loops are worst at the upper limit of control, 0.1 Hz. If it were assumed that all the residual motion were at 0.1 Hz, much worse than actual observation, the rate calculates to 10^{-4} arcsec/sec, or 10^{-4} deg/hour. This is reasonably comparable to the objective for angular rate

which was 10^{-4} deg/hr at the slightly higher frequency of 1 rad/sec, or 0.16 Hz.

There is a motion reduction by the high frequency control loops which is greatest at the corresponding natural frequency of each degree-of-freedom, and generally is effective from about 0.2 - 8 Hz. The result is that under normal, quiescent conditions such as is expected to be maintained during precision test operations, a stability of about 10^{-8}g or better over most of the 0.1 to 20 Hz frequency band of the linear motions.

10.2 Motion Excitation

The objectives were met of obtaining Iso-pad motion excitation limits for high-frequency (HF) angular and translation modes, and the low-frequency (LF) tilt modes. As discussed above, there are presently no provisions for LF translation and azimuth modes. Typical frequency response plots have been covered in the foregoing, and the application of Iso-pad motion excitation to numerous examples, e.g., precision instrument tests, has been covered.

10.3 Associated Research

During a large part of the time that the Iso-pad has been in existence, the Iso-pad has been used as a research tool to support other tasks. There have been an assortment of tasks, both of a type requiring a very stable test base and of those which required a very precisely known excitation. A number of these 'supported tasks' were briefly described in the previous section. The researchers of the supported tasks included USAFA faculty members, cadets, new graduates, contractors, and FJSRL. Wear-out components, e.g., the pneumatic diaphragms, have been replaced, and the Iso-pad status is one of 'readiness' for use as a research tool.

11. RECOMMENDATIONS

The 'official' task objectives and final performances are about an order of magnitude short of the 10^{-9}g stability (desired) goals of a Holloman AFB proposed future test laboratory, and a 10^{-9}g potential stability was a sometimes considered objective for the FJSRL system. At this point, such an order of magnitude improvement does not appear feasible within the bounds of the Iso-pad facility options. Certainly meeting such an objective would require the potential for reconsideration of the complete facility, including facility location for a minimum seismic noise on the base, control of facility design to minimize cultural noise effects, system configuration and structure to optimize primary natural frequencies of the K/M system and separation, to very high frequency, of structural resonances, instrumentation, and method of applying forces to counter any residual motion.

It was not considered appropriate that specific recommendations on an effort toward the 10^{-9}g stability goals be attempted here. However, for sake of completeness, it is noted that an effort is underway by Holloman AFB toward such a future test capability. The HAFB effort is supported by USAF Academy faculty, departments DFEM (Engineering Mechanics) and DFCE (Civil Engineering) and to a lesser extent by FJSRL. Disclosure of the plans for this effort was made by HAFB at the October 1979 Biennial Guidance Test Symposium.

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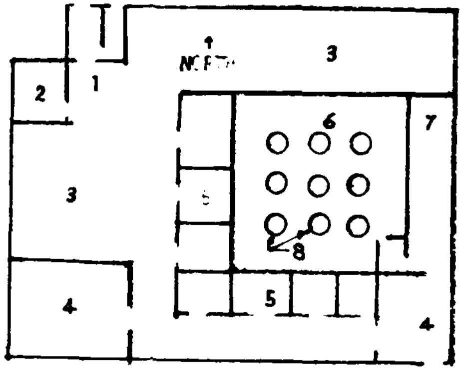
Figure 1. Layout of G&C Lab



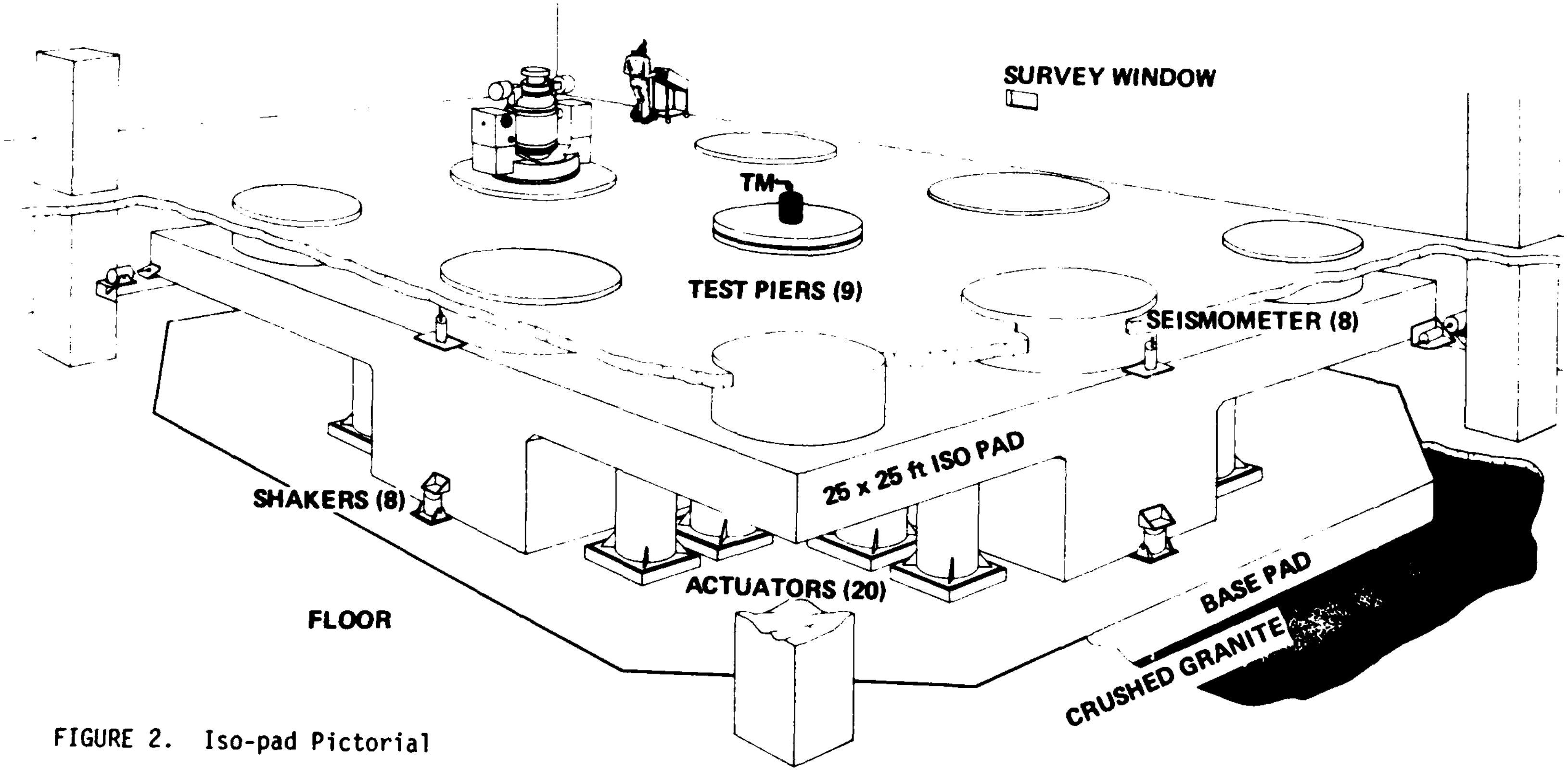


FIGURE 2. Iso-pad Pictorial

Figure 3. Vertical Transmissibility of Passive Iso-pad

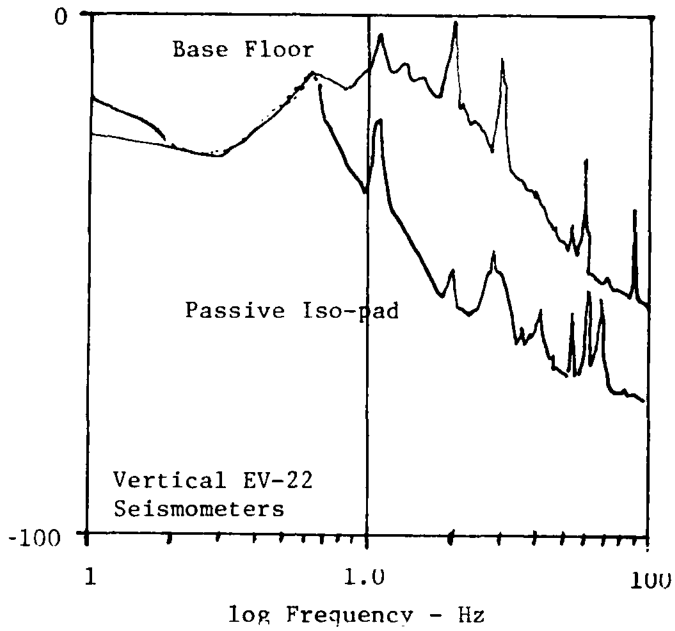


Figure 4. Quiescent Motion Comparison

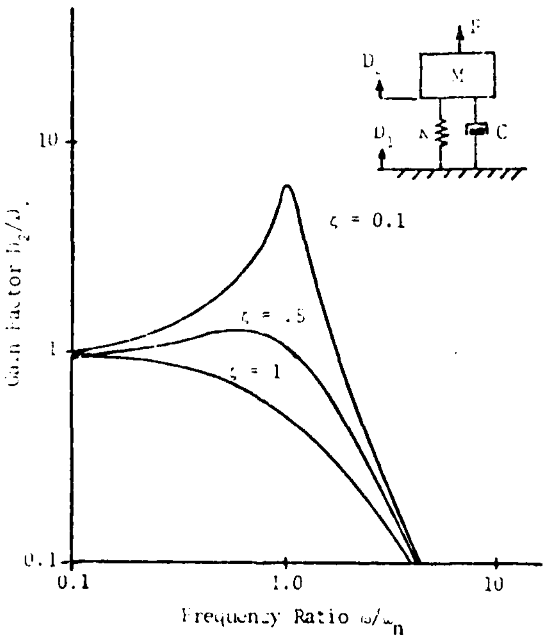


Figure 5. Isolation to Base Motion Inputs

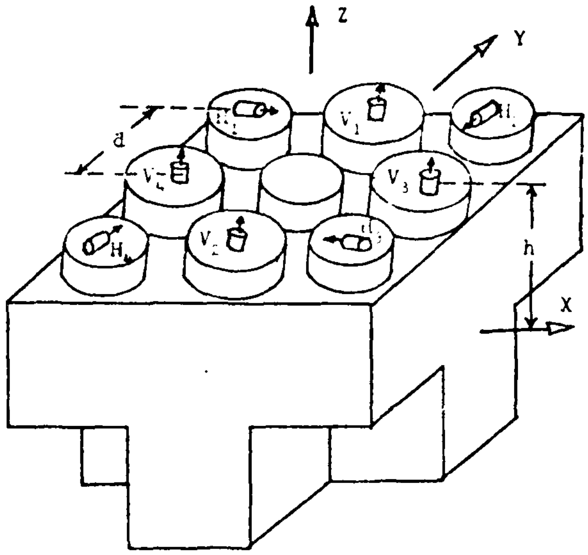


Figure 6. Orientation of Seismometers

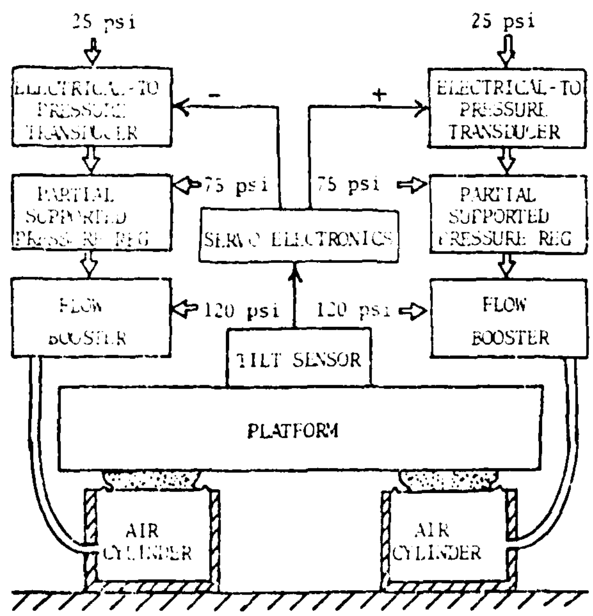


Figure 7. Tilt Sensor Control Loop

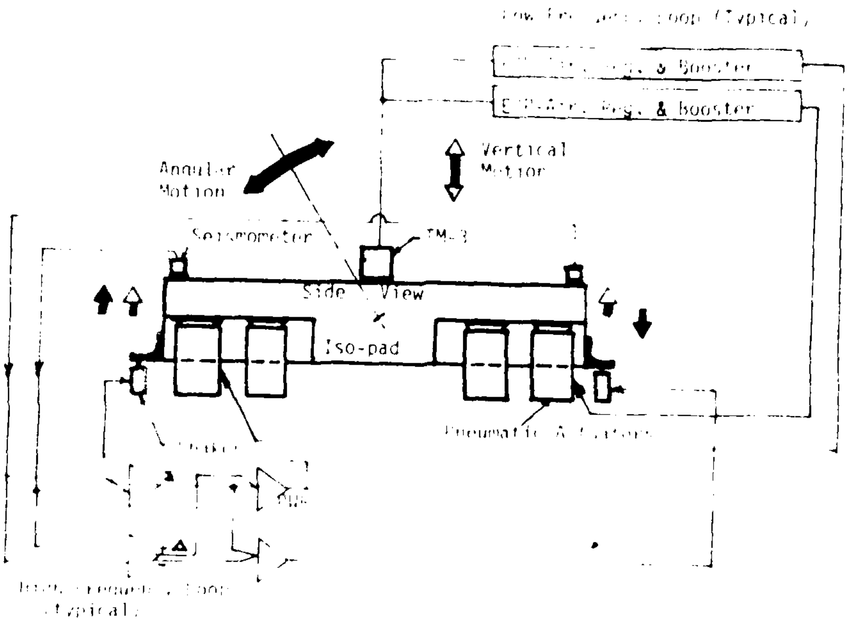


FIGURE 8. Iso-pad Vertical Excitation

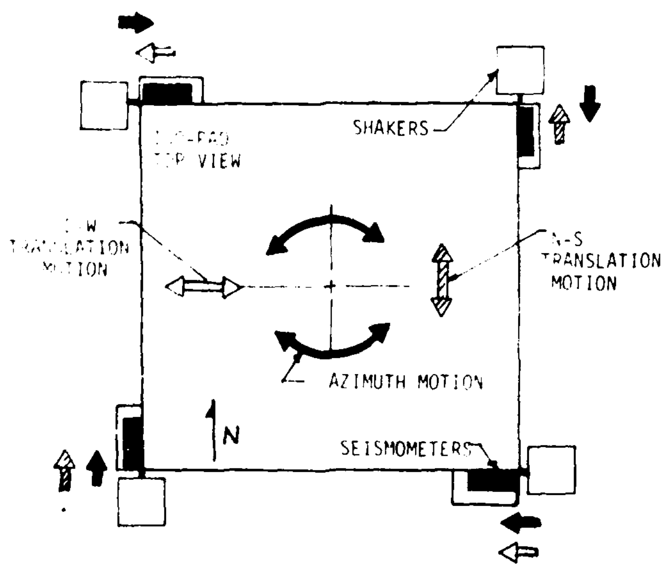


FIGURE 9. Iso-pad Horizontal Excitation

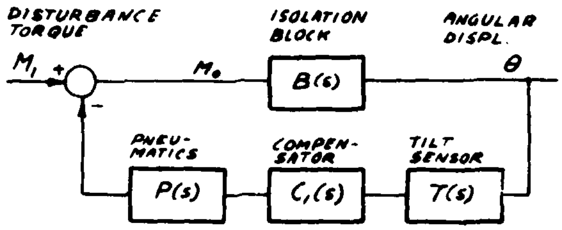


Figure 10. Block Diagram for Low Frequency Tiltmeter Loop

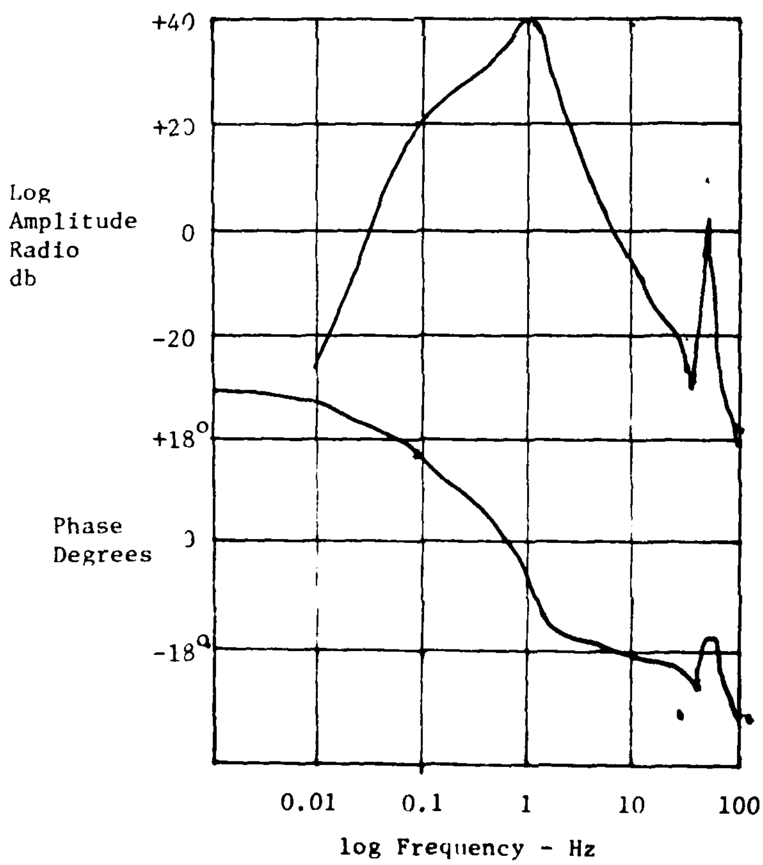


Figure 11. Open Loop Response of the High Frequency Angular Control Loop

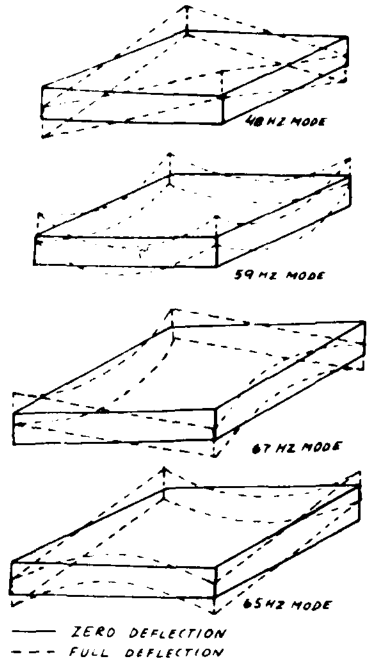


Figure 12. Structural Resonance Modes of the Seismic Isolation Block

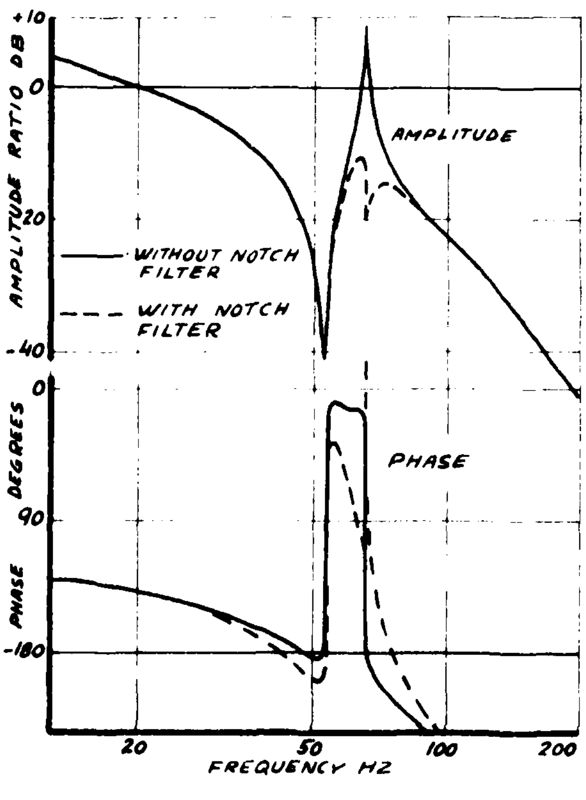
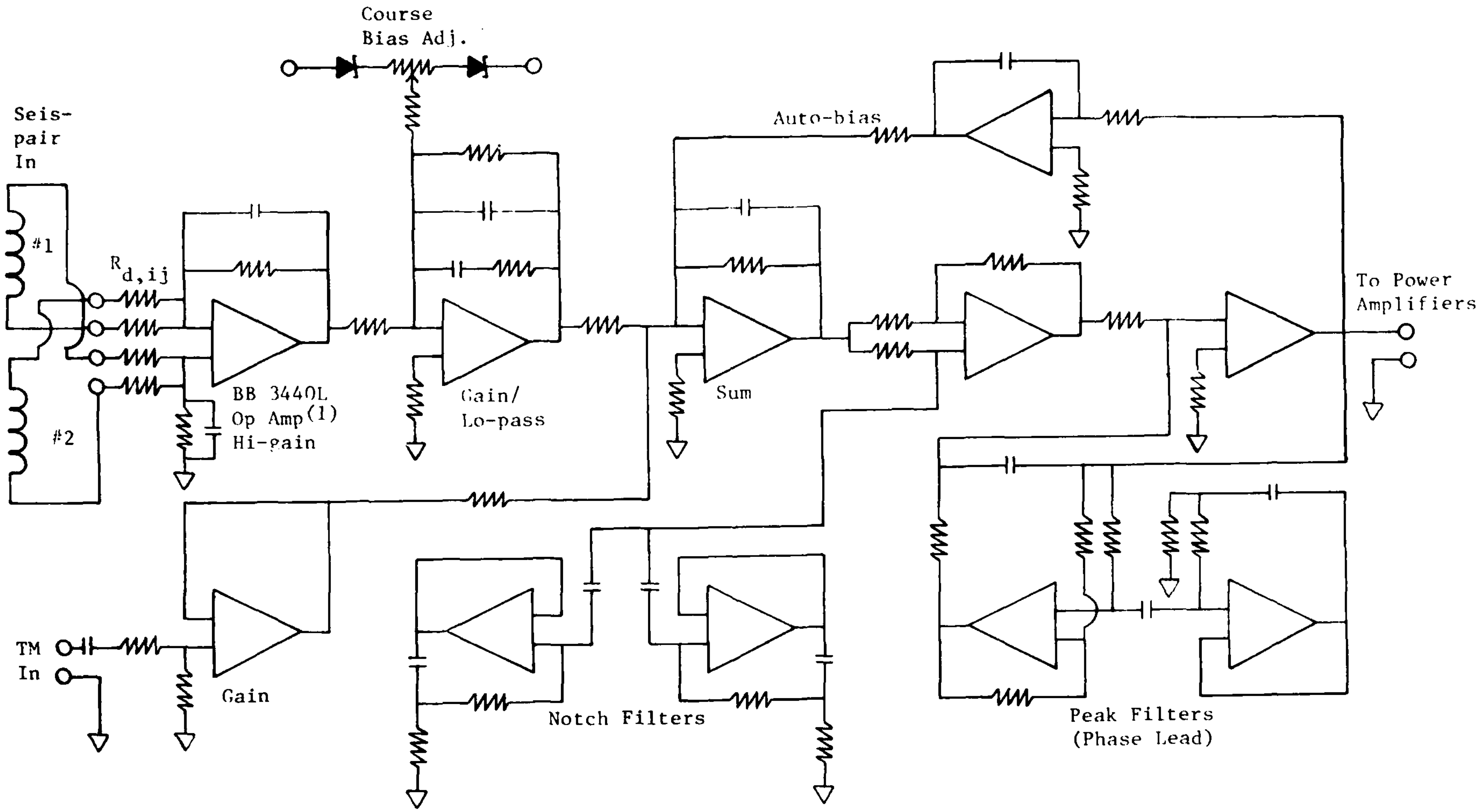


Figure 13. Open Loop Transfer Function of Angular Control System Showing Block Structural Resonance



(1) All other amplifiers are Op 07's.

Figure 14. High Frequency Servo Amplifier/Compensation (Typical)

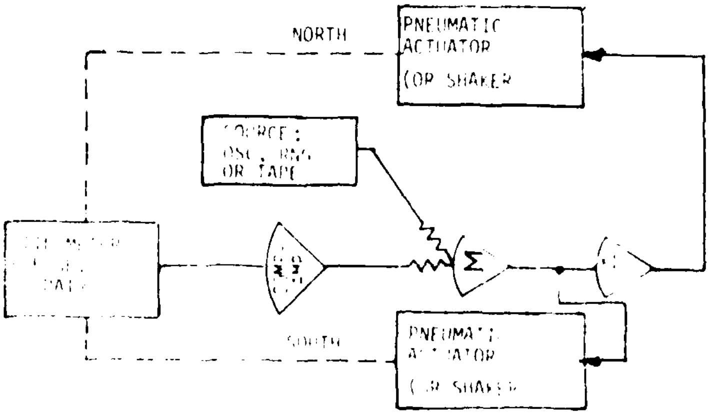


FIGURE 15. Excitation Schematic (Typical)

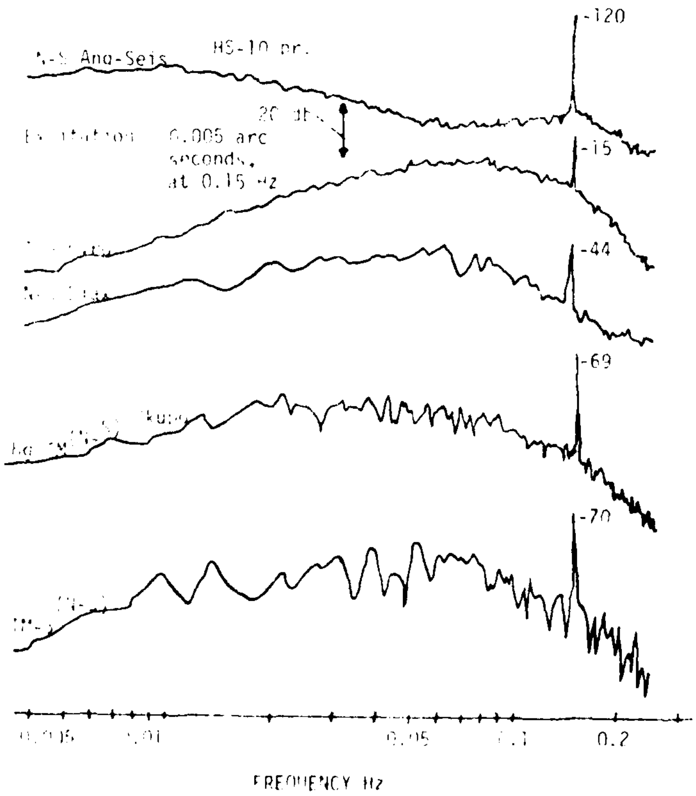


FIGURE 16. Sensors output to 0.005 arc second excitation

Figure 17. Closed Loop Response of High Frequency Angular Control Loop and Tiltmeter Augmented Loop

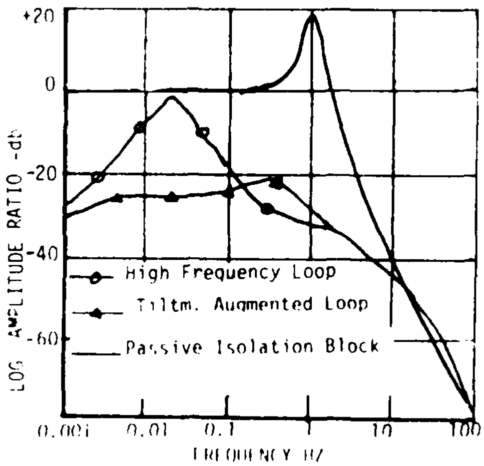
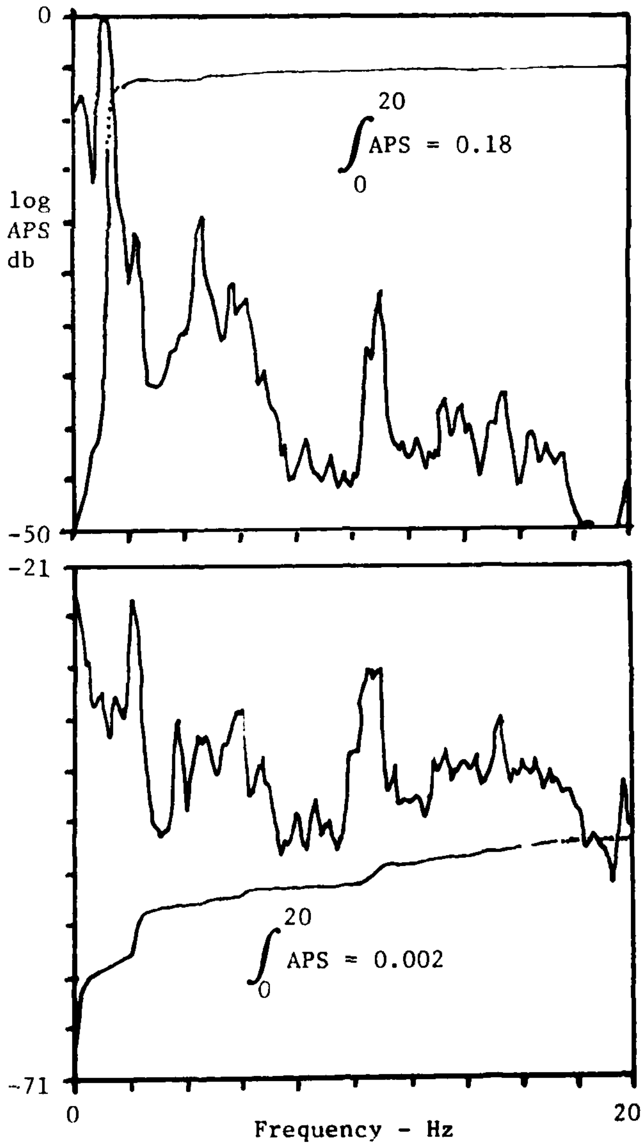


Figure 18. Motion Auto Power Spectra, E-W Angular

a. Servo OFF

b. Servo ON



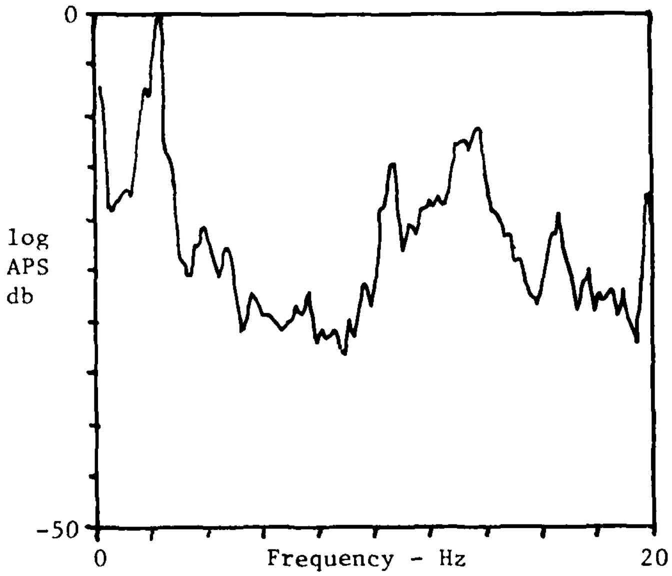


Figure 19. Motion Auto-Power Spectra, N-S Angular with Servo ON

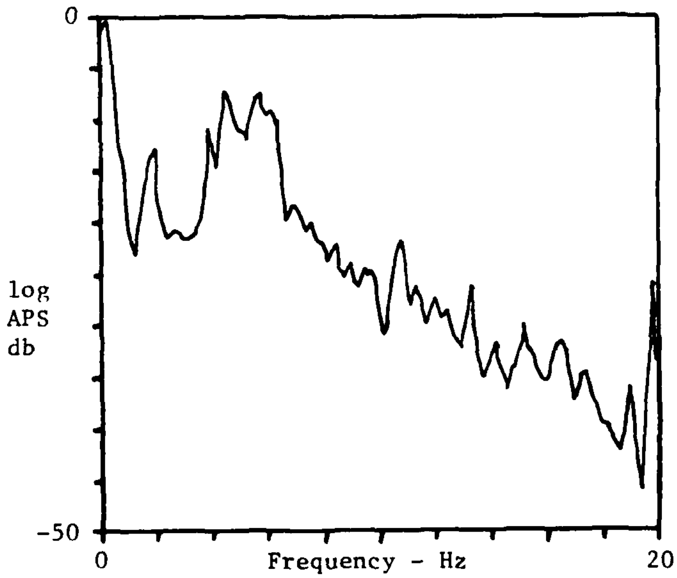


Figure 20. Motion Auto-Power Spectra, Vertical with Servo ON

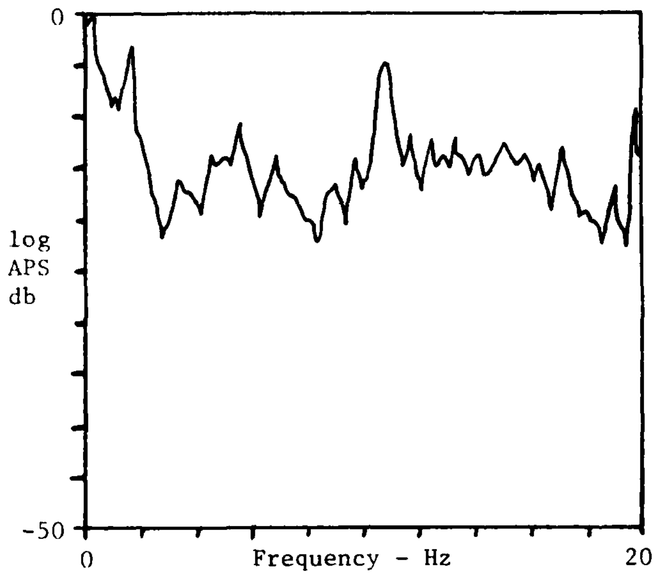


Figure 21. Motion Auto-Power Spectra, Azimuth with Servo ON

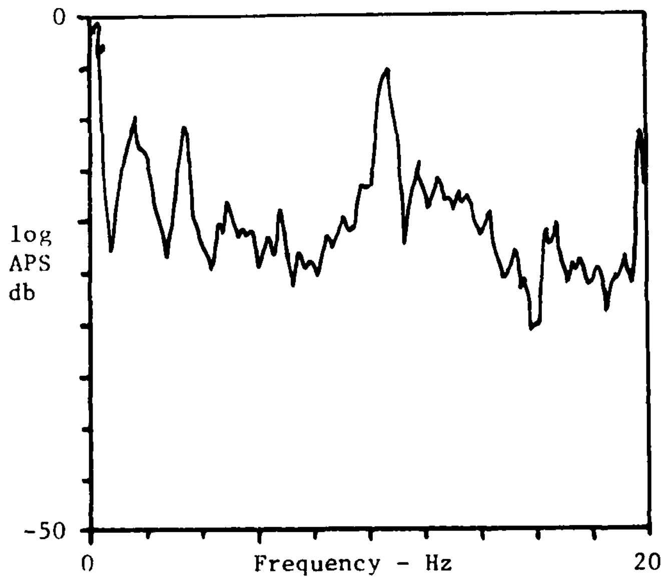
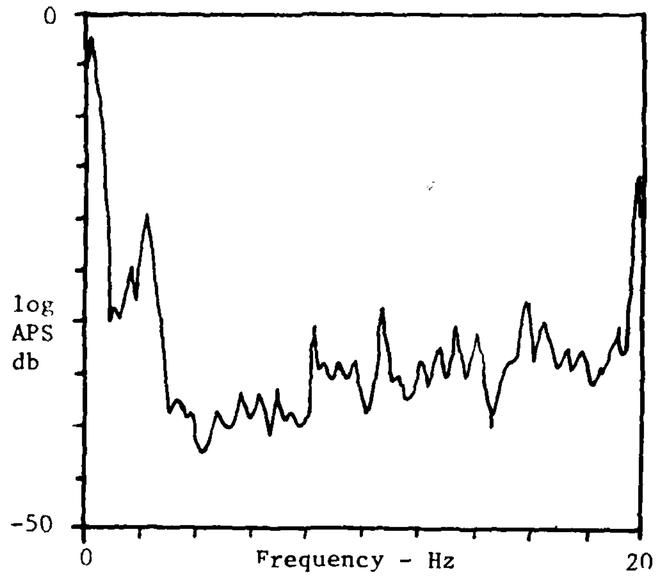


Figure 22. Motion Auto-Power Spectra, N-S Linear with Servo ON

Figure 23. Motion Auto-Power Spectra, E-W Linear with Servo ON



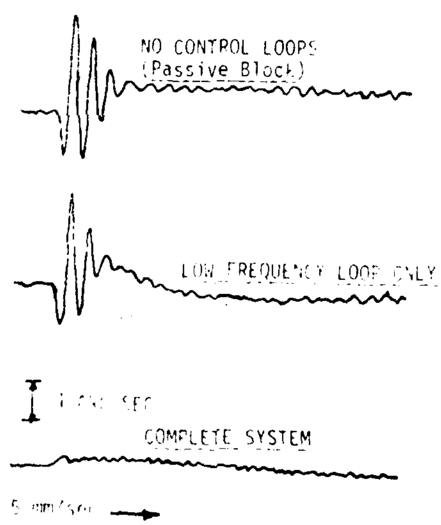


FIGURE 24. Response of the N-S Axis Angular Control System to a 60 lb-ft Step Torque Input

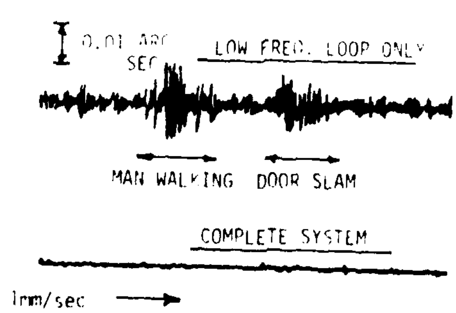


FIGURE 25. Response of the N-S Axis Angular Control System to Ambient Disturbances

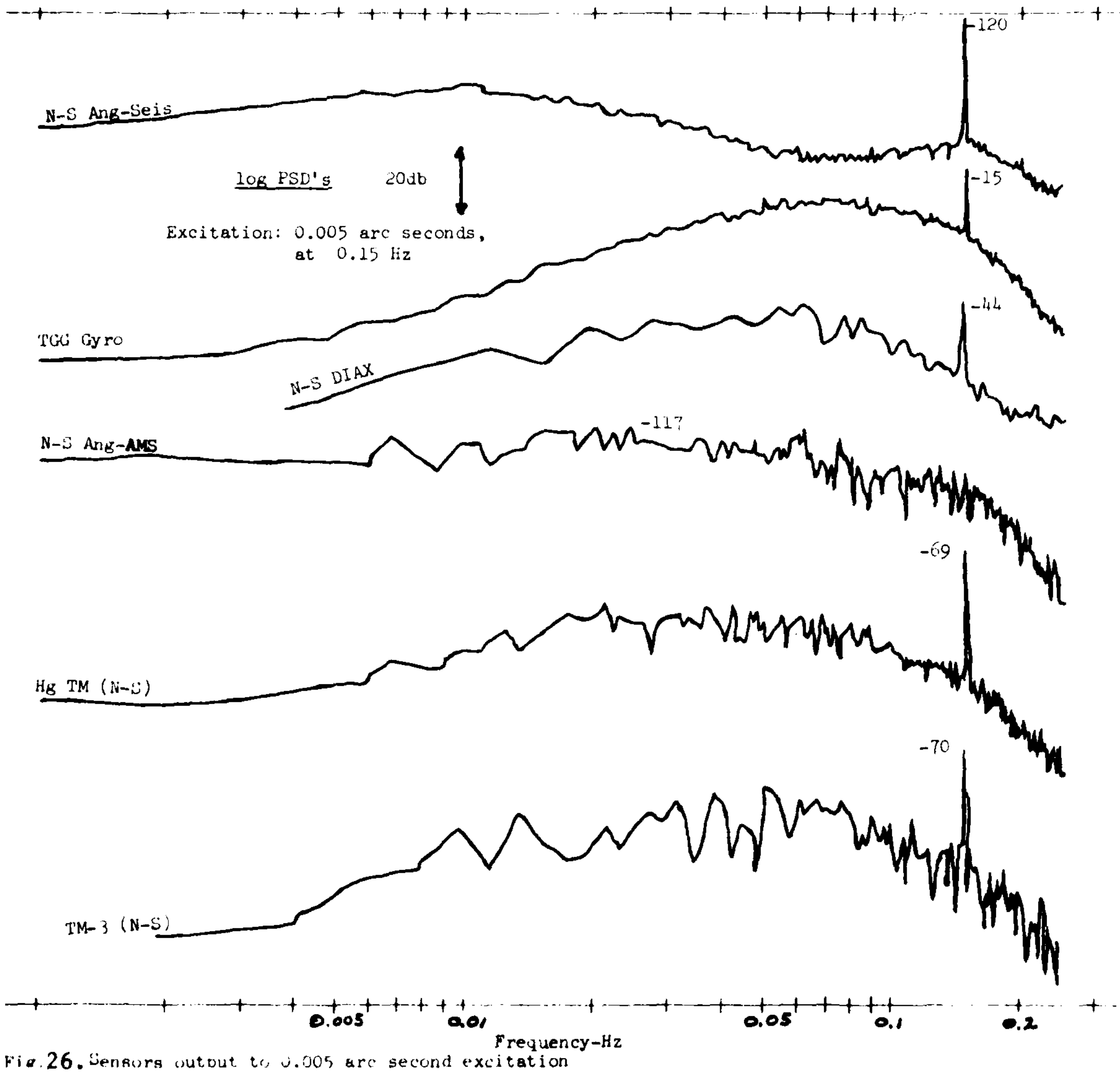


Fig.26. Sensors output to 0.005 arc second excitation

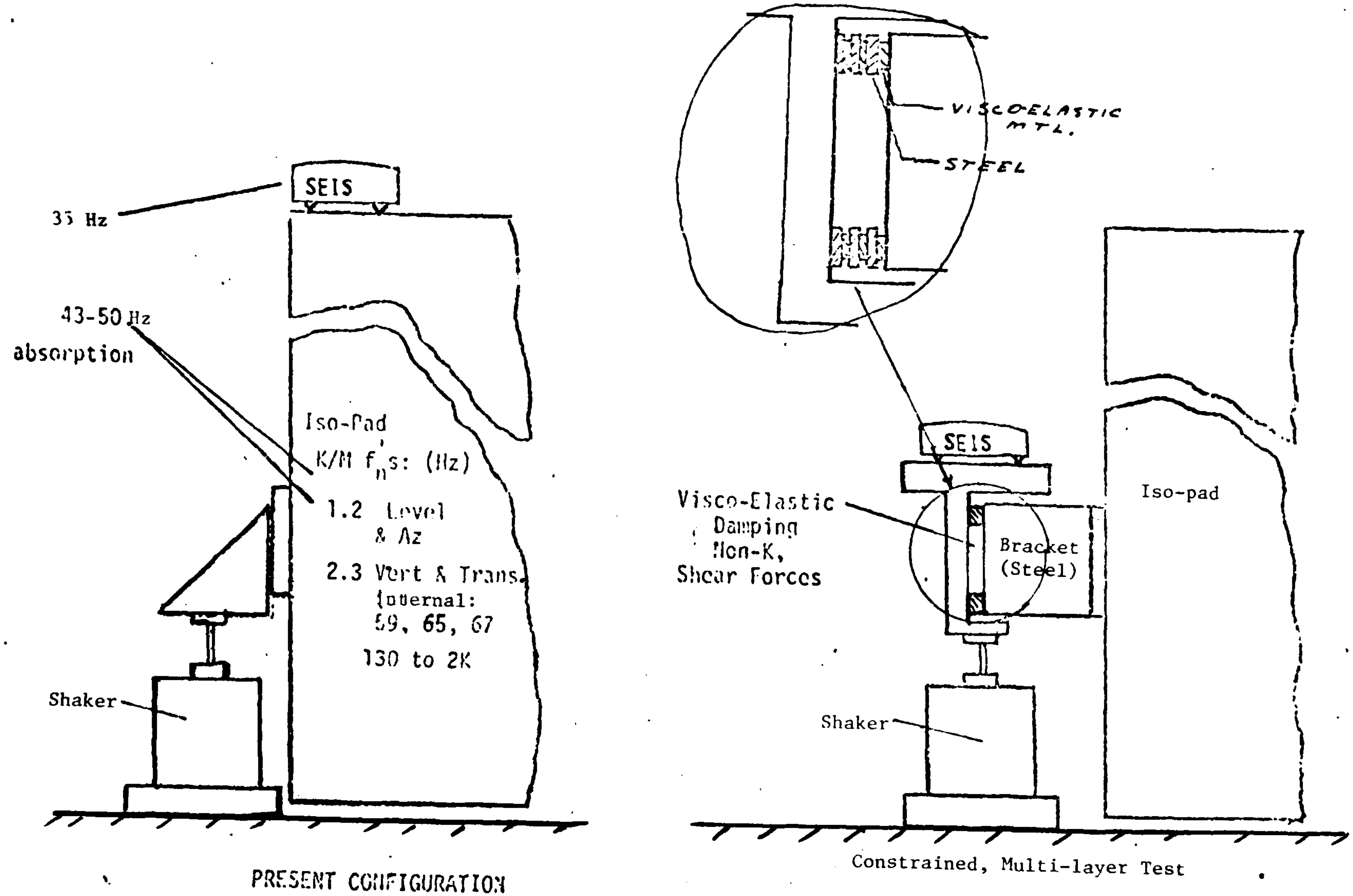


Figure 27. Damping Decoupling Test Configuration

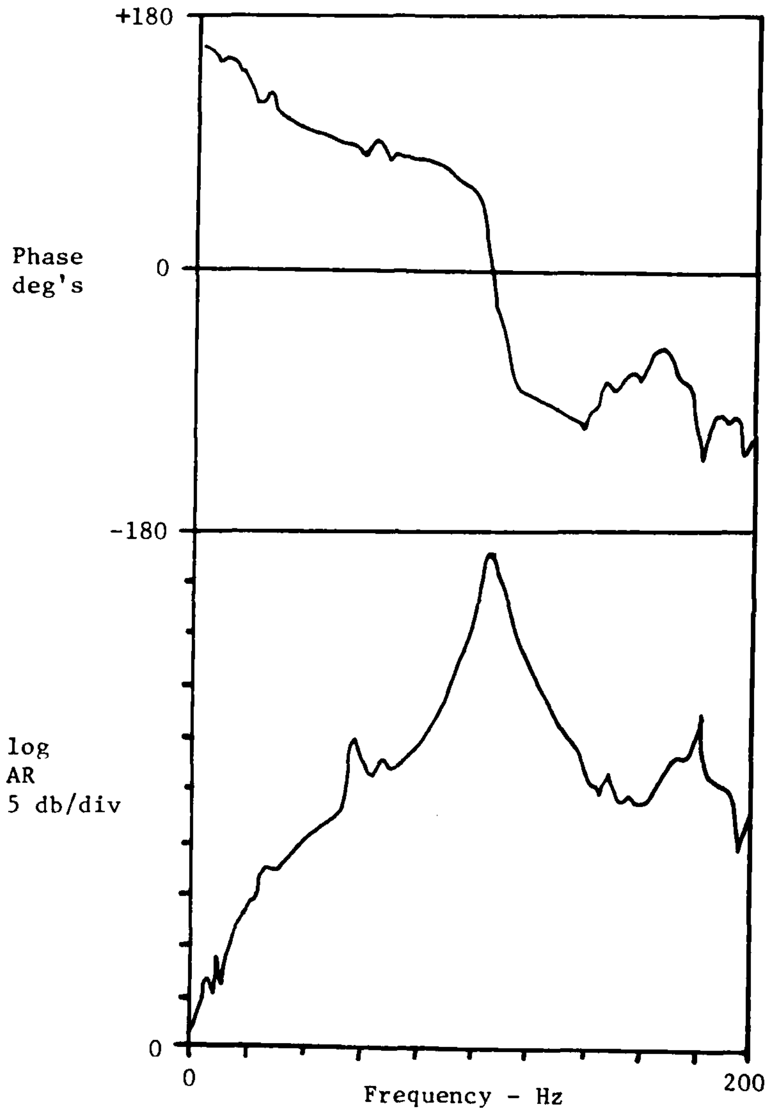


Figure 28. Damping Decoupling Response

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